RADIATION IN SUPERCONDUCTING MAGNETS AT SUPERCOLLIDERS

pp- and accelerator-related radiation loads in IR components at LHC, LHC-2, SLHC, VLHC-1 and VLHC-2

Nikolai Mokhov
Fermilab

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OUTLINE

- Introduction
- Source terms
- Comparing machines: intensity and luminosity arithmetic
- IR protection against pp-collision products
- Simulated radiation loads in inner and outer triplets
- Dipole-first IR layout
- IR protection against operational and accidental beam loss

INTRODUCTION

The Large Hadron Collider (LHC) will produce pp collisions at $\sqrt{s}$=14 TeV and luminosity $\mathcal{L}$=10^{34} cm^{-2}s^{-1}. The interaction rate of 8×10^{8} s^{-1} represents a power of almost 900 W per beam, the majority of which is directed towards the low-β insertions, with about one third of the power carried out by neutrals in the very forward direction. At future supercolliders under consideration – LHC-2, SLHC, VLHC-1 and VLHC-2 – the IP power is up to a factor of ten higher. The quadrupole fields sweep the secondary particles into the coils preferentially along the vertical and horizontal planes, giving rise to local peak power density ε_{max} that can substantially exceed the quench limits. Corresponding dynamic heat load can exceed the cryogenics capacity. Build-up of radiation defects can drastically reduce component lifetime. Hands-on maintenance is rather difficult if all components in the entire region are highly radioactive. Another serious concern is operational and accidental beam losses. The corresponding IR layout, magnet design and materials, and an appropriate set of collimators and absorbers must provide adequate mitigation of these problems.

SOURCE TERMS

1. **pp collisions:** radiation $\sim \sigma_p \times \mathcal{L}$, $\mathcal{L}$=10^{34} to 10^{35} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$.
2. **Operational beam loss:** tails from collimators and beam-gas scattering, radiation $\sim$ beam power (Q = 0.35 to 3.2 GJ) $\times$ loss rate.
3. **Accidental beam loss:** abort kicker prefire / unsynchronized beam abort, radiation $\sim$ beam power (Q = 0.35 to 3.2 GJ) $\times$ loss rate. Up to 10% loss in IR if not intercepted in the abort section.

INTENSITY AND LUMINOSITY ARITHMETIC

Machine	E (TeV)	I, 10^{14}	Q (GJ)	$\sqrt{S}$	$\mathcal{L}$, 10^{34}	σ_p(mb)	10^{16} (int/10yr)
Tevatron	0.98	0.1	0.0016	1.96	0.01	60	
LHC	7	3.1	0.35	14	1	80	4
LHC-2	7	4.8	0.54	14	4.7	80	19
SLHC	7	9.6	1.08	14	10	80	40
VLHC-1	20	9.7	3.20	40	1	90	4.5
VLHC-2	100	2.0	3.20	200	2	105	10.5

LHC rule:

$\mathcal{L}_{10yr}$ = (0.1+1/3+2/3+7) $\times \mathcal{L}$ at 180 days/yr

10yrs = 5×10^7 s $\rightarrow$ 500 fb^{-1}

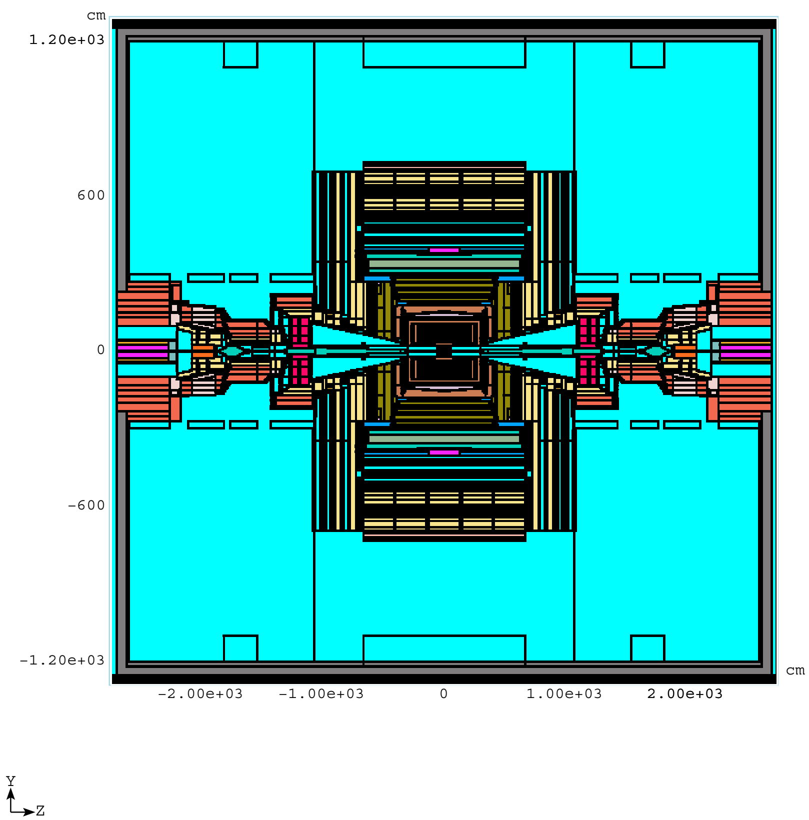
8×10^8 int/s at 80 mb and 10^{34} $\rightarrow$ 4×10^{16} int/10yr

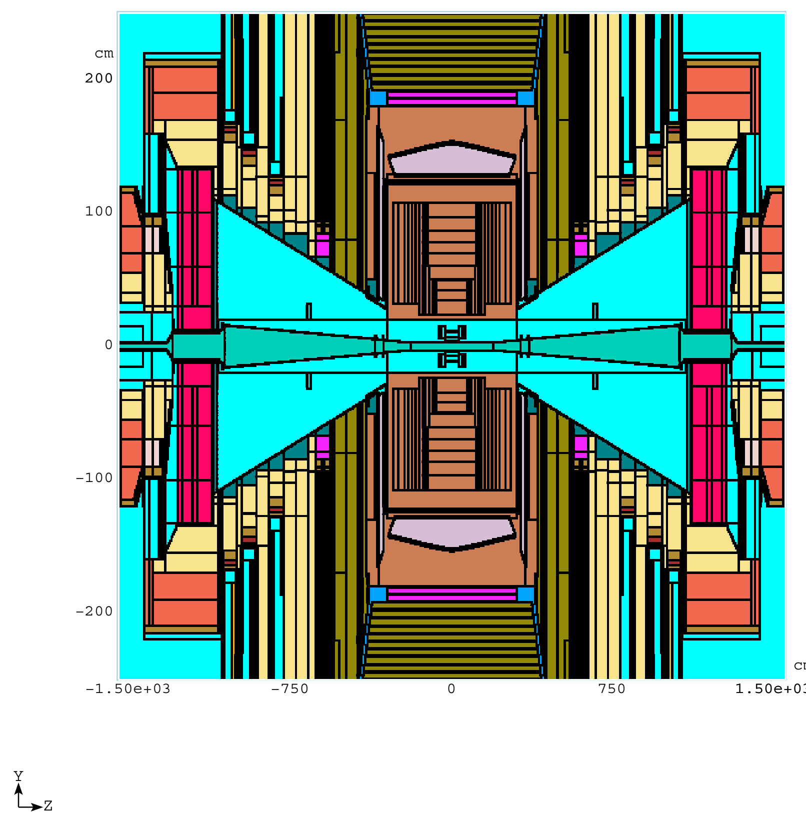
PP-EVENT AT 14, 40 AND 200 TEV

Average multiplicity, energy and transverse momentum in pp-collisions as simulated with DPMJET-3

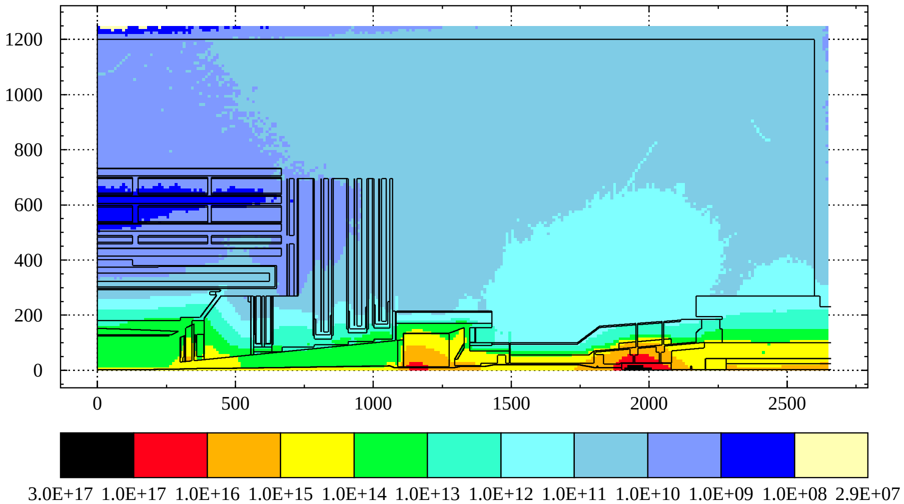
	$\sqrt{S}$ (TeV)	14	40	200
$< n >$	p	2.63	3.09	4.03
	n	2.13	2.61	3.55
	π^0	35.49	44.76	62.91
	All charged	72.93	92.26	129.85
	Total	126.97	160.76	226.36
E (TeV)	p	3.58	9.84	49.34
	n	1.42	4.22	21.10
	π^0	2.48	7.09	35.63
	All charged	8.61	24.43	121.41
	Total	14.00	40.00	200.00
$< p_t >$ (GeV/c)	$\pi^{\pm}$	0.46	0.50	0.61

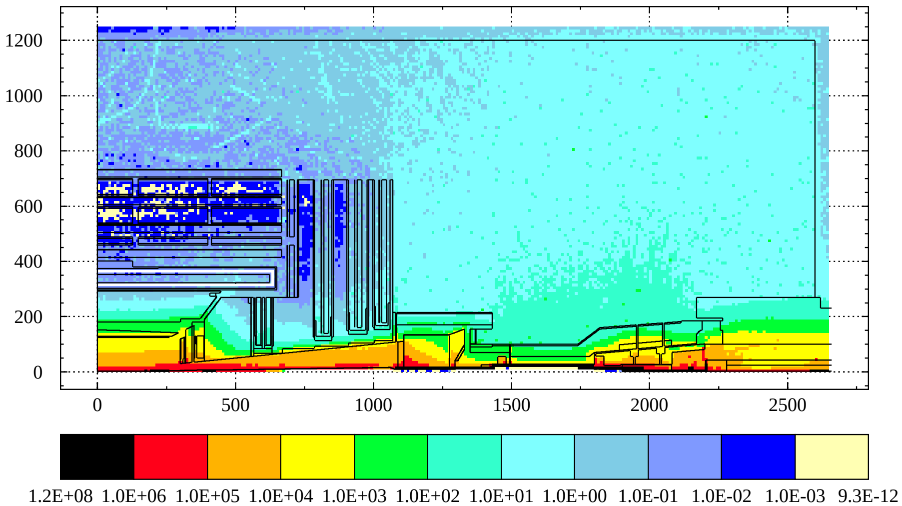
CMS COLLIDER DETECTOR IN FLUKA AND MARS





NEUTRON FLUENCE AND DOSE IN CMS AT 10^{34}





Courtesy M. Huhtinen

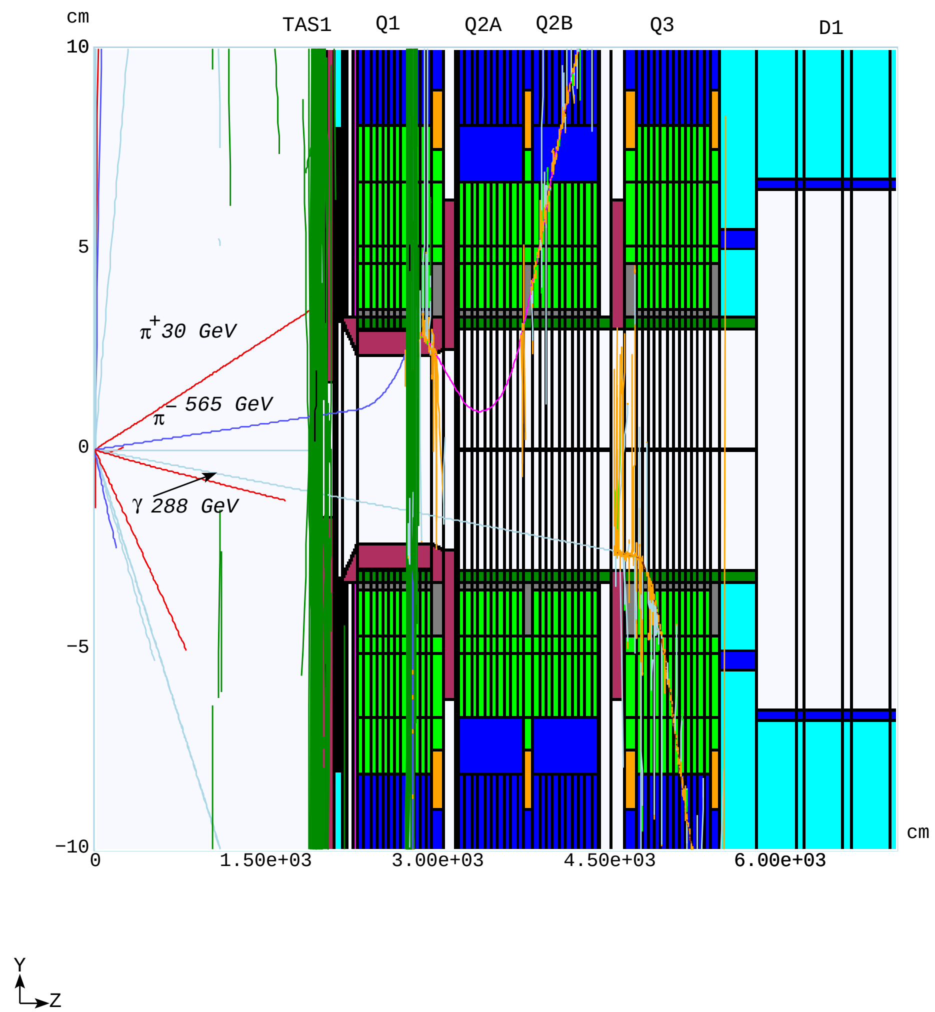
PEAK RADIATION LOADS IN DETECTOR

Peak 10-year fluence (cm^{-2}) and dose (Gy) in inner tracker and HF calorimeter at 14, 40 and 200 TeV (preliminary)

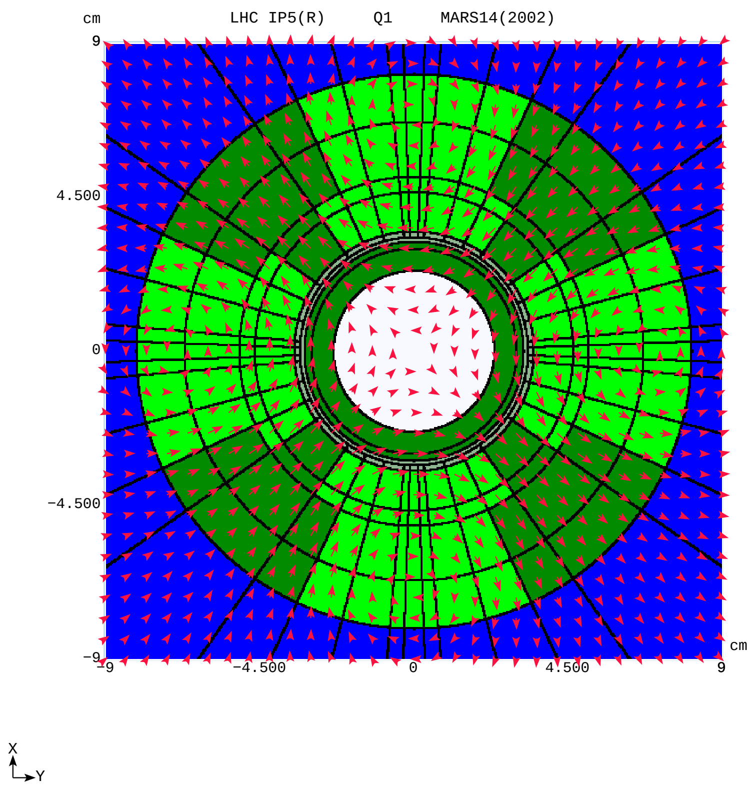
Detector	Value	SLHC	VLHC-1	VLHC-2
SVX	F_n	2×10^{15}	2×10^{14}	8×10^{14}
	F_{chh}	8×10^{16}	8×10^{15}	1×10^{16}
	D	1.5×10^{7}	1.5×10^{6}	3×10^{6}
Tracker	F_n	1.5×10^{15}	2×10^{14}	6×10^{14}
	F_{chh}	1.5×10^{15}	2.5×10^{14}	6×10^{14}
	D	8×10^{5}	8×10^{4}	2×10^{5}
Fin	F_n	1.8×10^{16}	2×10^{15}	4×10^{15}
	F_{chh}	8×10^{14}	1×10^{14}	2.5×10^{14}
	D	2×10^{6}	3×10^{5}	5×10^{5}
HF	F_n	1.5×10^{17}	2.1×10^{16}	4.8×10^{16}
	F_{chh}	7×10^{15}	1.2×10^{15}	2.5×10^{15}
	D	2.5×10^{7}	3.5×10^{6}	1×10^{7}

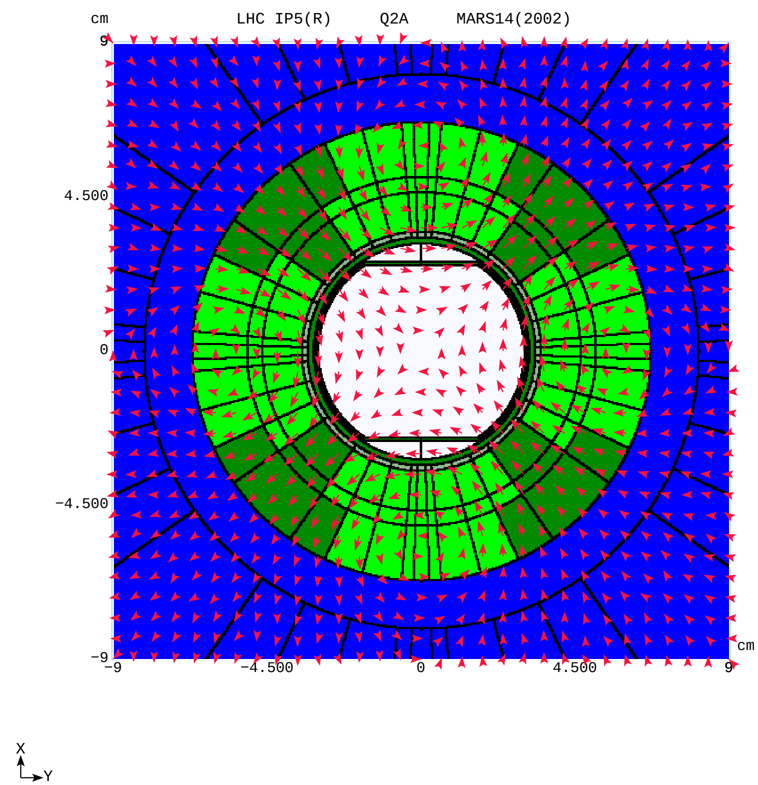
Residual dose rates at SLHC!!!

IR COMPONENT PROTECTION



KEK AND FNAL QUADRUPOLE MODELS





PROTECTION SYSTEM DESIGN CONSTRAINTS

1. Design luminosity: $\mathbf{10^{34}\ cm^{-2}s^{-1}}$ at LHC through $\mathbf{10^{35}\ cm^{-2}s^{-1}}$ at SLHC.
2. Geometrical aperture: Keep it larger than "n1 = 7" for injection and collision optics, including closed orbit and mechanical tolerances.
3. Quench stability: Keep peak power density ε_{max}, which can be as much as an order of magnitude larger than the azimuthal average, below the quench limit with **a safety margin of a factor of 3.**
4. Radiation damage: With the above levels, the estimated lifetime exceeds 7 years even in the hottest spots.

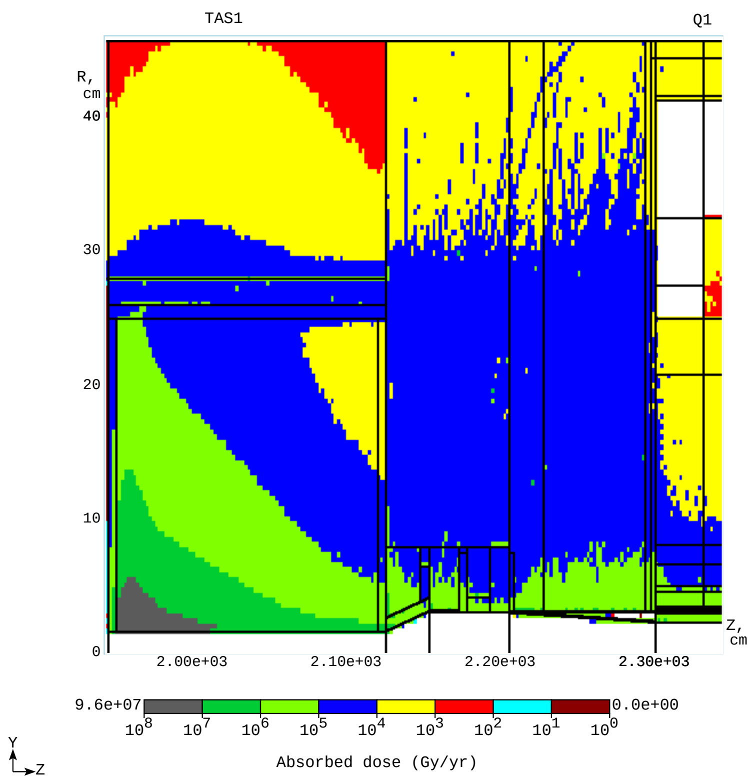
5. Quench limit: For many years, the estimated quench limit for the LHC high-gradient quadrupoles was 1.2 mW/g. Tests of porous cable insulation systems and recent calculations concerning the insulation system to be used in the Fermilab-built LHC IR quadrupoles (MQXB) have shown that up to about **1.6 mW/g** of heat can be removed while keeping the coil below the magnet quench temperature.
6. Dynamic heat load: Keep it below **10 W/m**.
7. Hands-on maintenance: Keep residual dose rates on the component outer surfaces below **0.1 mSv/hr**.

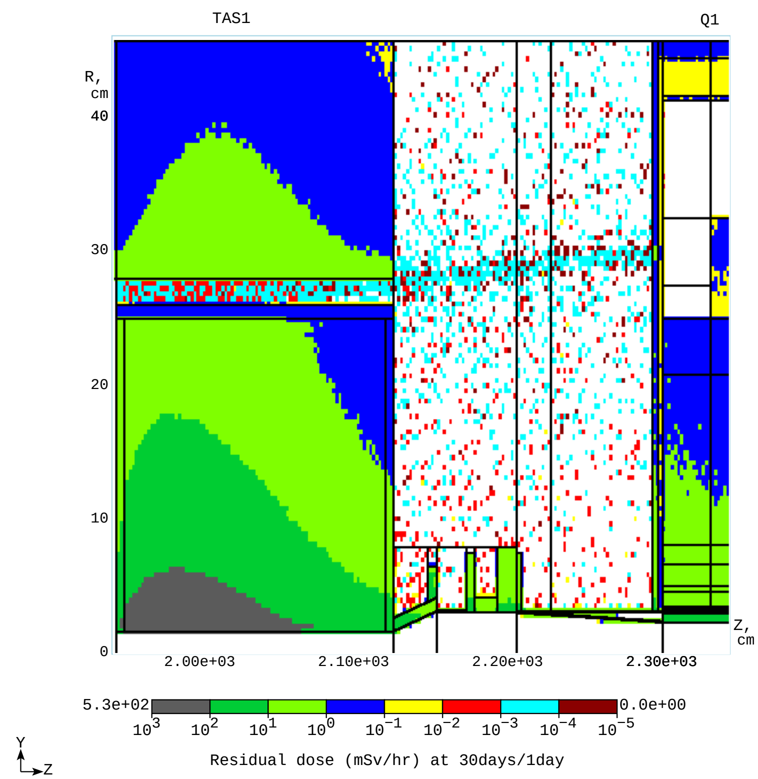
LHC IP1/5 PROTECTION SYSTEM

A set of absorbers on each side of the IP1 and IP5 has been designed over the years on the basis of comprehensive MARS calculations. It includes:

- The TAS front copper absorber at L=19.45 m (1.8 m long, 34-mm ID, 500-mm OD).
- A 7-mm thick stainless steel (SS) liner in Q1.
- The SS absorber TASB at L=45.05 m (1.2-m long, r=33.3-60 mm).
- A $\sim$3-mm thick SS liner in the Q2A through Q3.
- 40-cm long SS masks at L=23.45 m, r=250-325 mm to protect the Q1 slide bearings.
- The neutral particle 3.5-m copper absorber TAN at 140 m.
- The 1-m long TCL SS collimator at 191 m from IP.

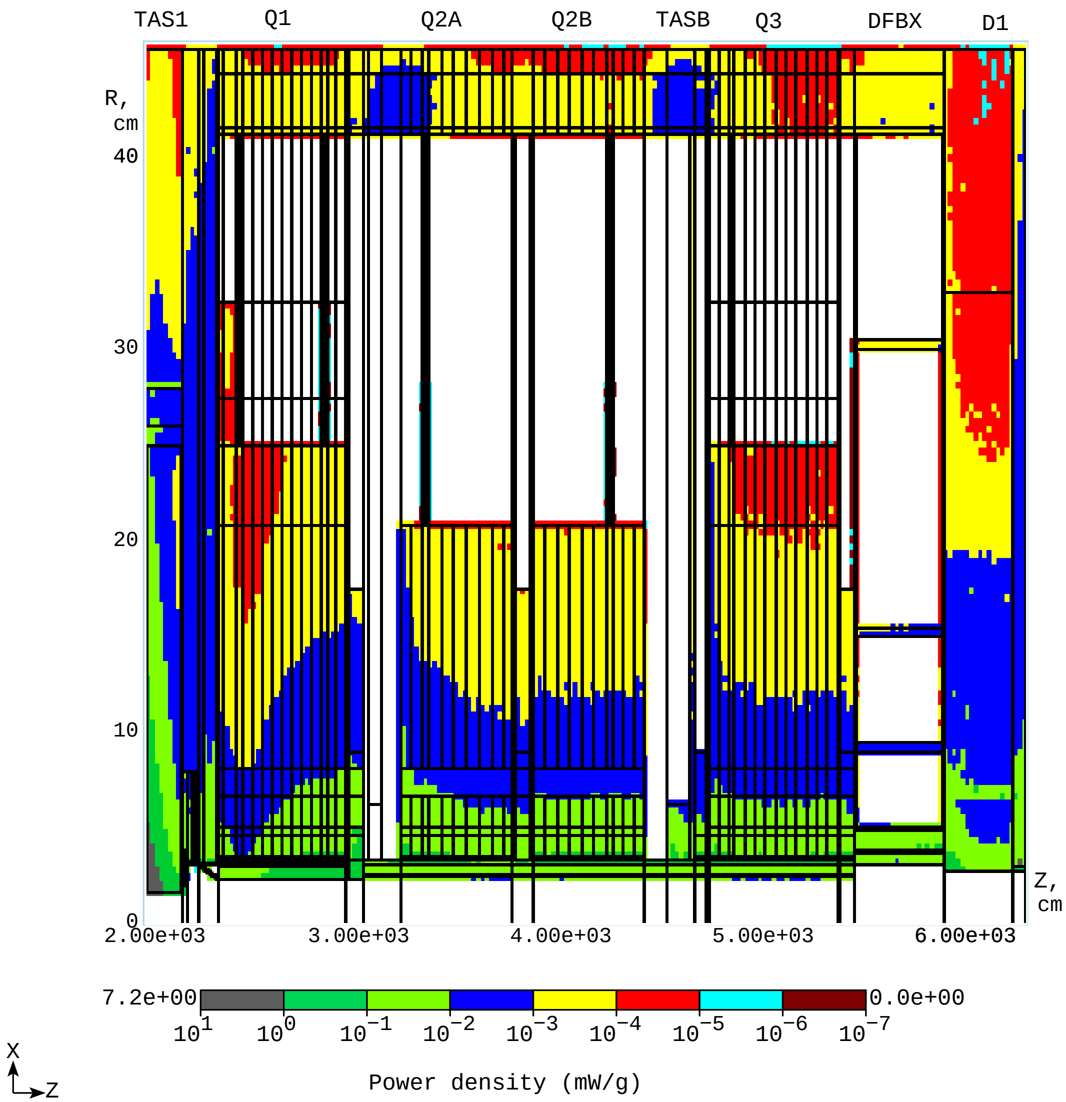
FRONT ABSORBER TAS



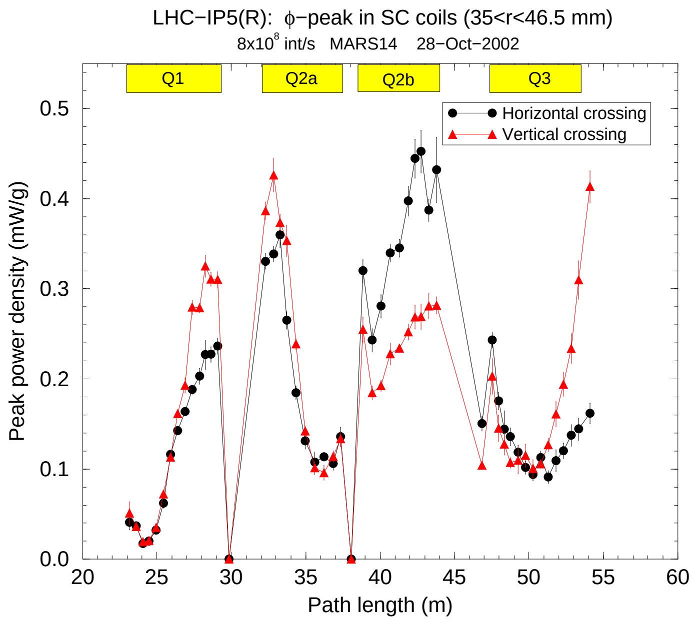


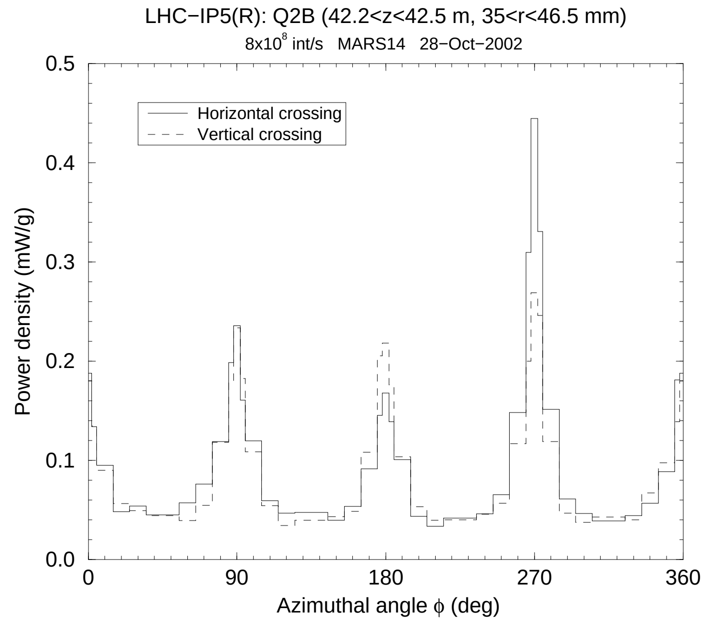
Azimuthally averaged absorbed dose in Gy/yr (left) and residual dose rate on contact after 30-day irradiation and 1-day cooling (right) in mSv/hr.

POWER DENSITY ISOCONTOURS



POWER DENSITY: LONGITUDINALLY AND AZIMUTHALLY

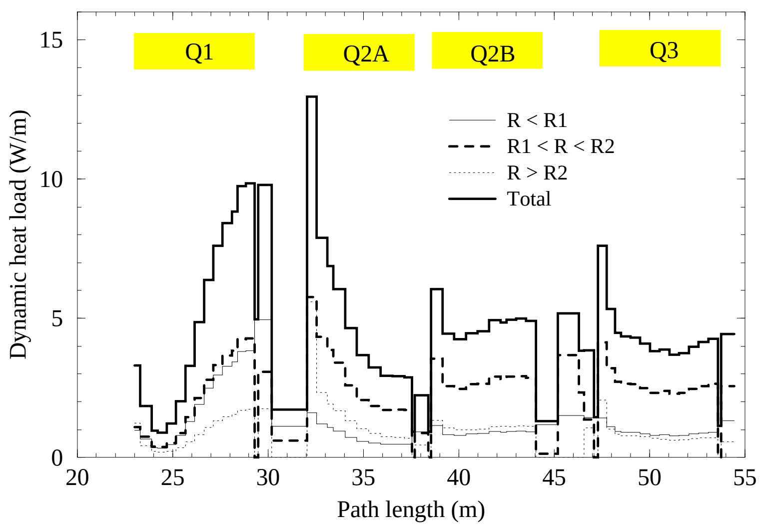


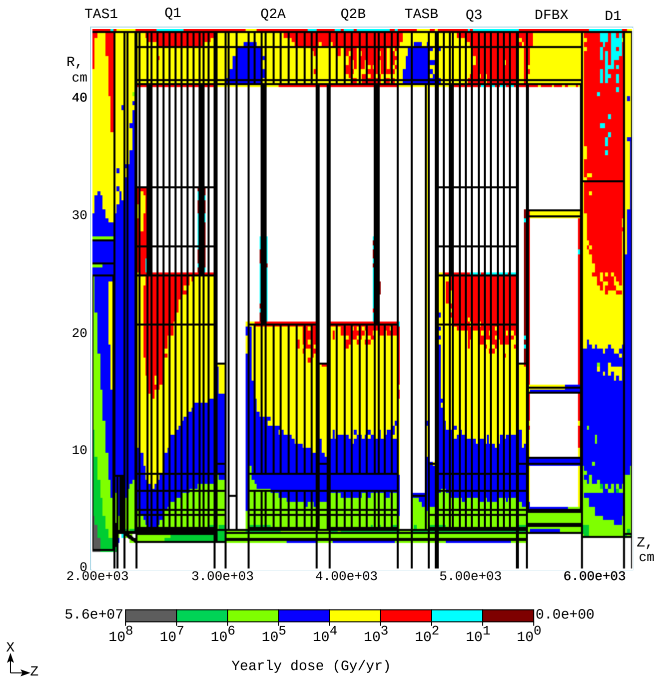


Peak power density *vs* L (left) and azimuthal distribution of power density at longitudinal peak in IP5 Q2b (right) in the fi rst radial bin of the SC coils.

The corresponding yearly dose can be estimated as D (MGy/yr) = 7.8 ε_{max} (mW/g), with the peak of 3.5 MGy/yr. Averaged over the coils it is about 100 kGy/yr, dropping down to several kGy/yr at the slide bearings supporting the yoke and further down with radius.

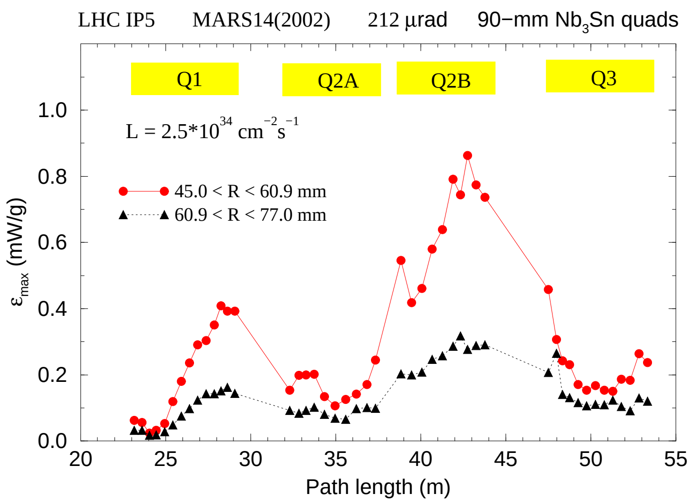
DYNAMIC HEAT LOAD AND DOSE AT LHC

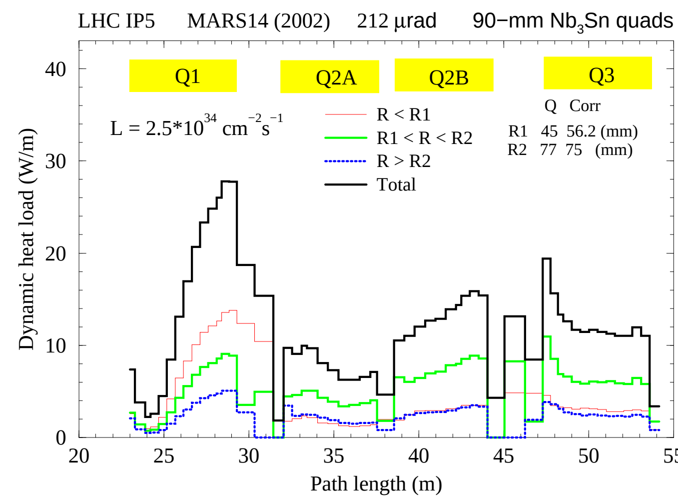




Power dissipation, R_1=35 mm, R_2=81 mm in Q1 and Q3 and R_2=67 mm in Q2a and Q2b (left) and azimuthally averaged yearly dose (Gy/yr) (right) in IP5.

RADIATION LOADS AT LHC-2





Peak power density in the SC coils (left) and dynamic heat load in radial layers (right) of the LHC-2 90-mm quads.

10-YEAR PEAK DOSE AND FLUENCES

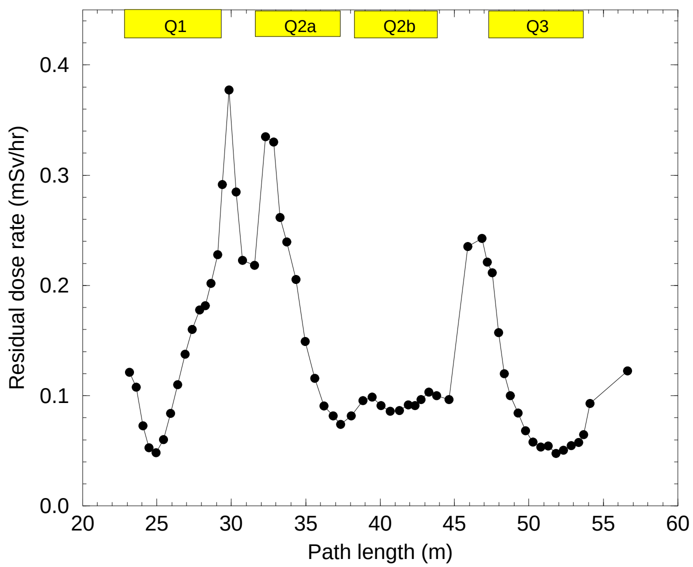
Peak dose D and neutron fluence $F_{>0.1\ MeV}$ in inner triplet SC coils accumulated over first 10 "LHC" years ($=5\times10^7$ sec). D (MGy/yr) = 50 ε (mW/g). Current designs. Very preliminary for VLHC-1 and VLHC-2.

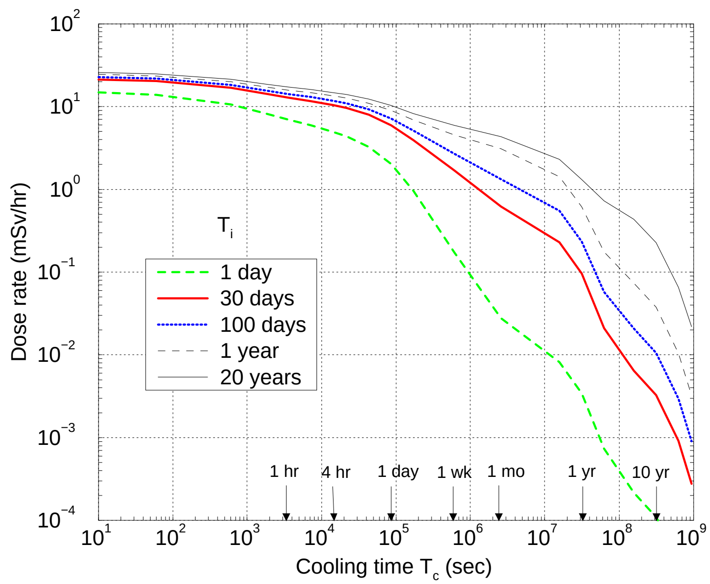
Machine	Component	D (MGy)	$F_{>0.1\ MeV}$, 10^{16} cm^{-2}
LHC	Quad Q2B	22.5	1.04
LHC-2	Quad Q2B	45.0	2.08
SLHC	Cosθ D1	650	30
SLHC	Block coil D1	55.0	2.54
VLHC-1	Quad Q2B	$\sim$30	$\sim$1.5
VLHC-2	Quad Q2B	$\sim$84	$\sim$4

Dynamic heat load P (W) to the LHC IP1/IP5 inner triplet components, $\times 10$ at SLHC.

Absorber TAS	184
Absorber TASB	5.7
Quadrupole Q1	30.7
Quadrupole Q2a	28.8
Quadrupole Q2b	26.6
Quadrupole Q3	27.7
Corrector MCBX1	6.9
Corrector MQSXA	2.0
Corrector MCBXA	3.1
Feedbox DFBX	6.92
Dipole D1	50
Absorber TAN	189
Dipole D2	2.0
Quadrupole Q4	0.4
Quadrupole Q5	1.8

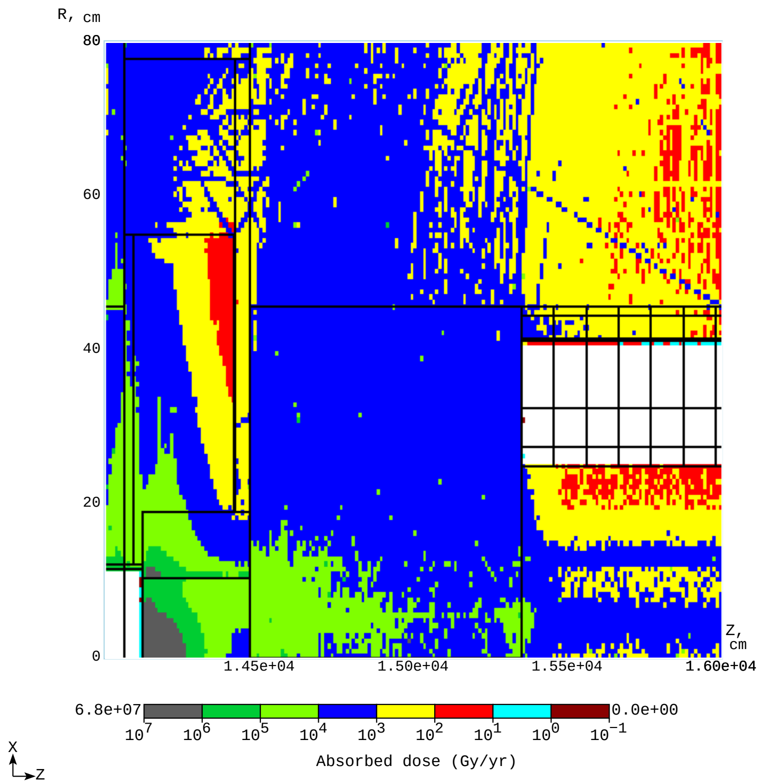
RESIDUAL DOSE IN INNER TRIPLET

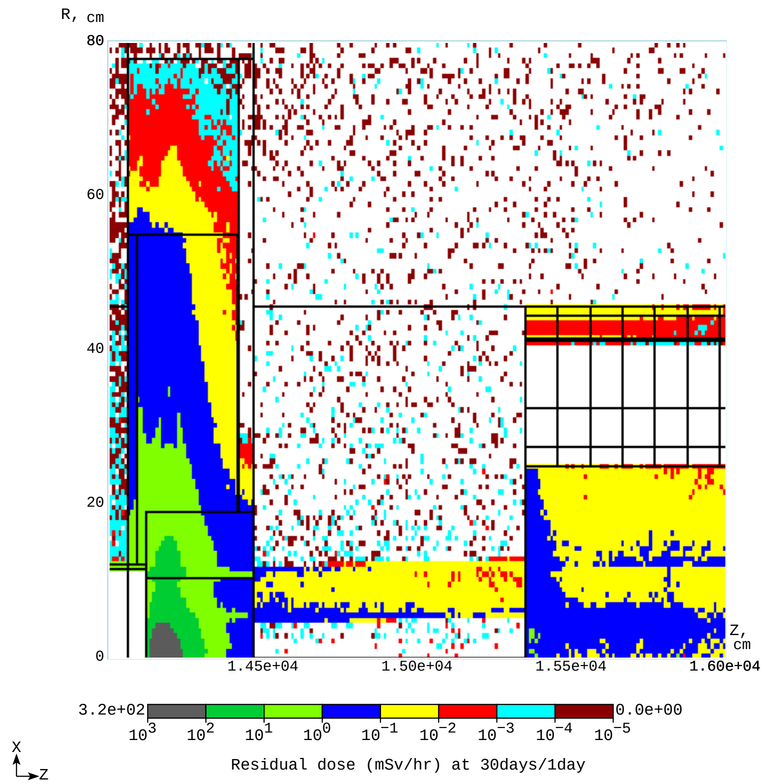




Residual dose rate (mSv/hr) on the inner triplet vacuum vessel after 30-day irradiation and 1-day cooling (left) and residual dose averaged over the IP1/IP5 quadrupole SC coils (all quads, all layers) *vs* irradiation and cooling times (right).

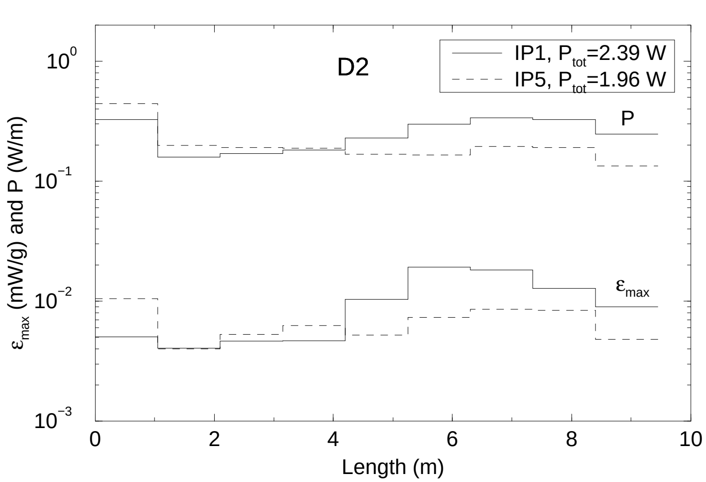
ABSORBED AND RESIDUAL DOSE IN TAN-D2

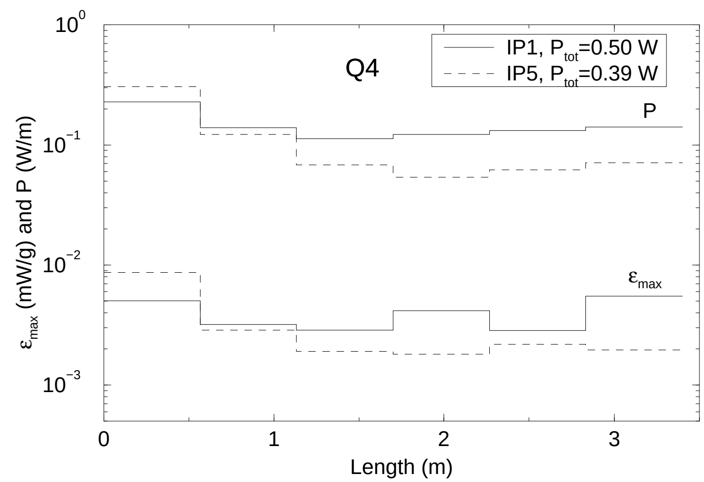




Azimuthally averaged yearly absorbed dose in Gy/yr (left) and 30day/1day residual dose in mSv/hr (right) in the IP5 TAN-D2 region.

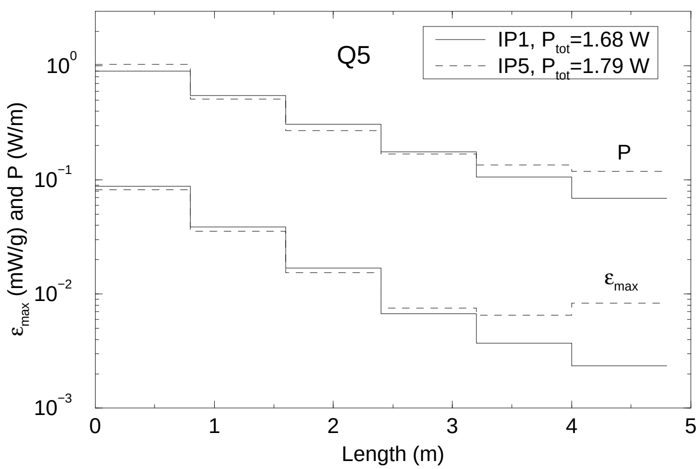
POWER DENSITY AND DYNAMIC HEAT LOAD IN D2 AND Q4

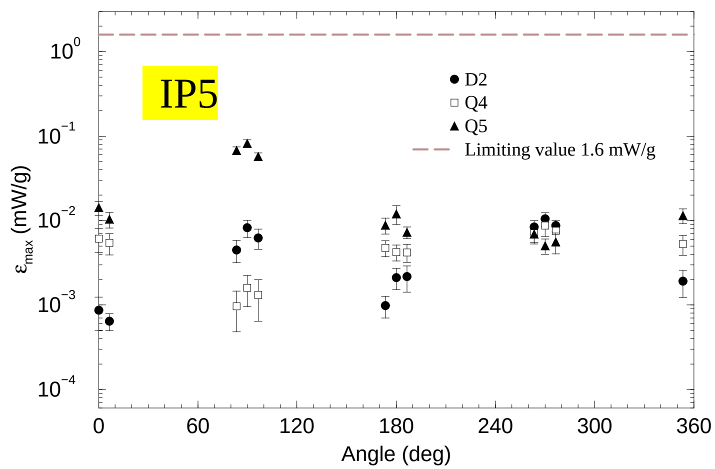




Peak power density ε_{max} and dynamic heat load *P vs* length in the IP1 and IP5 D2 separation magnet (left) and Q4 outer triplet quadrupole (right).

POWER DENSITY AND DYNAMIC HEAT LOAD

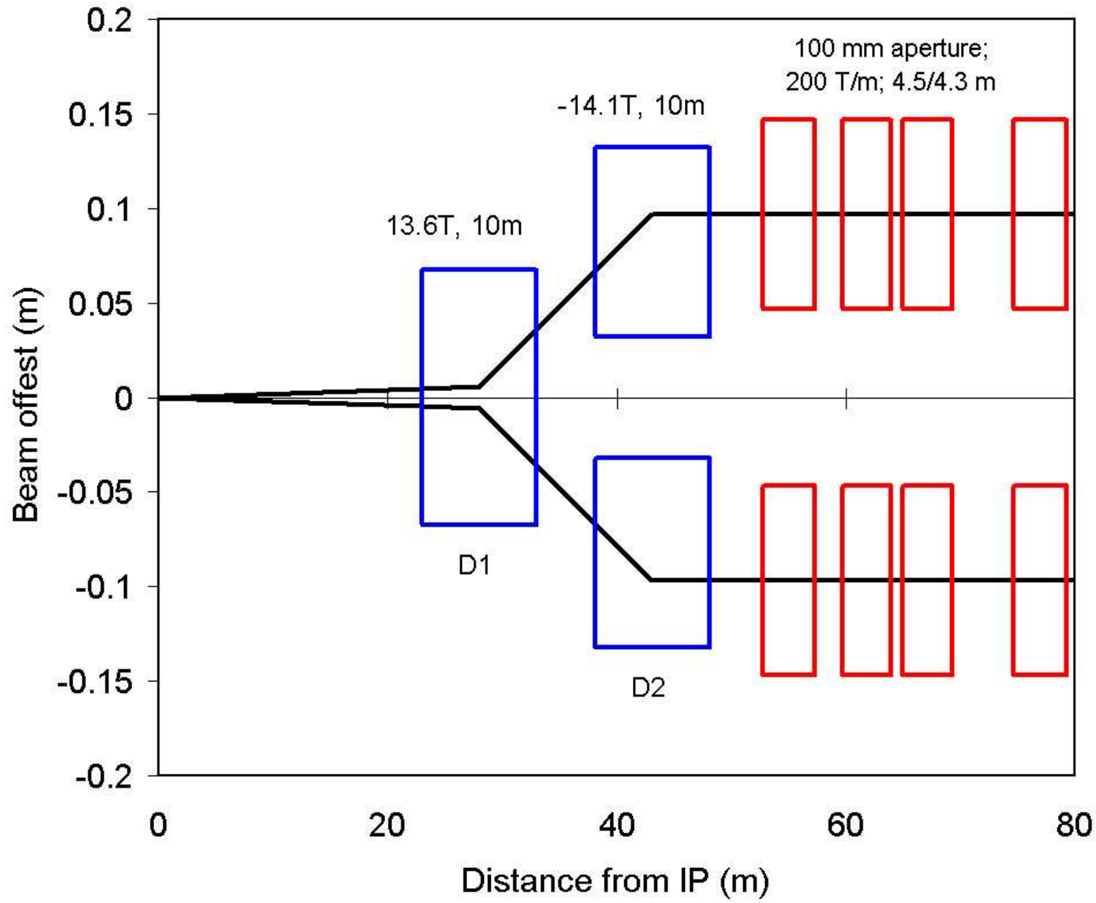




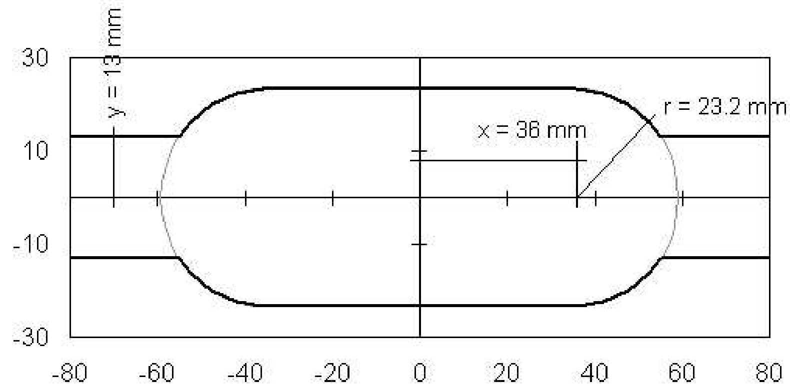
Peak power density ε_{max} and dynamic heat load *P vs* length in the IP1 and IP5 Q5 quad (left) and ε_{max} *vs* azimuthal angle (right).

This is with a 1-m TCL collimator at L=191 m. ε_{max} is about 1 mW/g without TCL!

SLHS: DIPOLE-FIRST IR LAYOUT

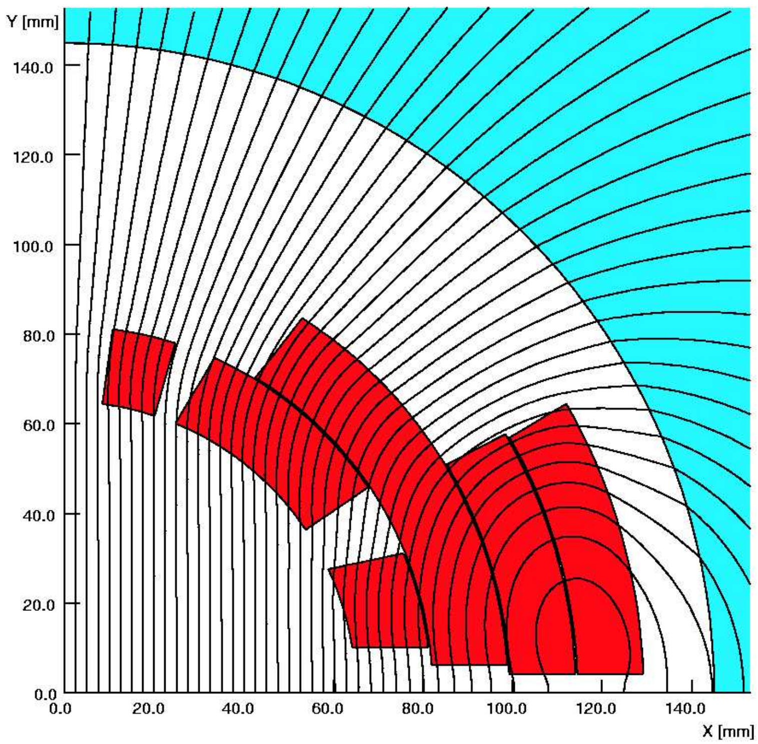


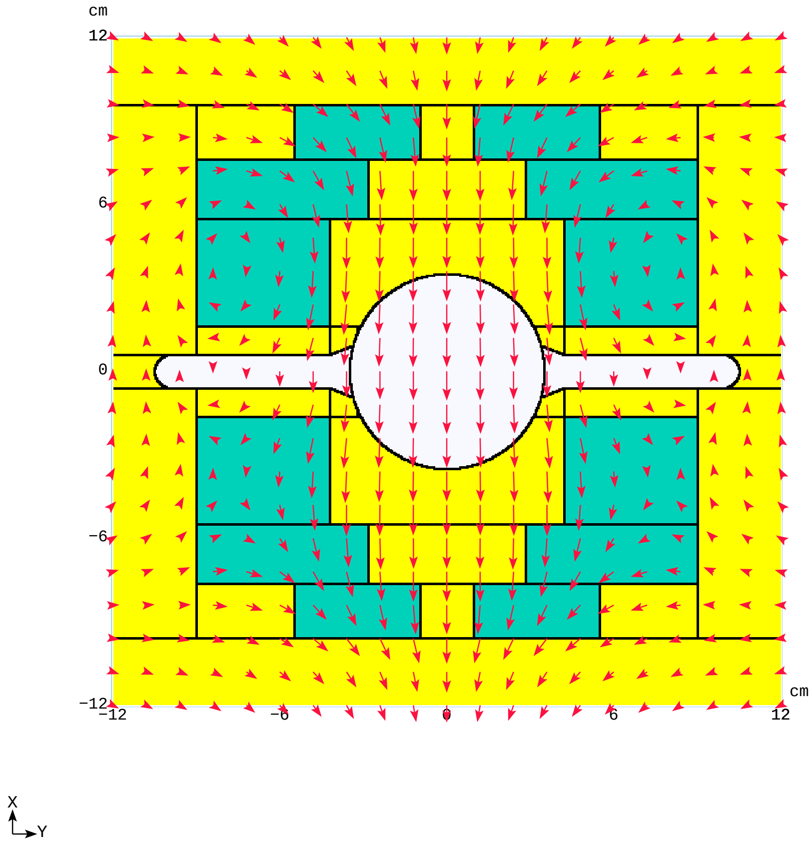
DIPOLE-FIRST APERTURE AND PARAMETERS



Parameter	Units	$\cos\theta$	Block
Coil aperture ID	mm	130	84
No. of layers	-	4	4
Quench bore field	T	15.8	15
Quench peak field	T	16.8	16.7
Conductor x-sec. area	cm^2	119.1	174.4
Yoke inner radius	mm	145	305
Yoke outer radius	mm	500	500

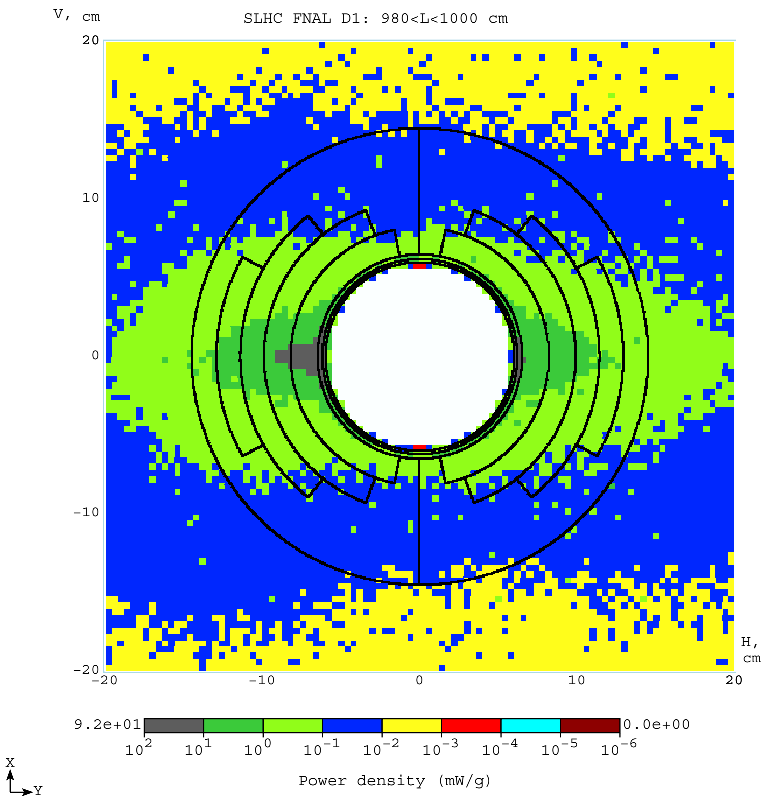
DIPOLE-FIRST MAGNET DESIGNS

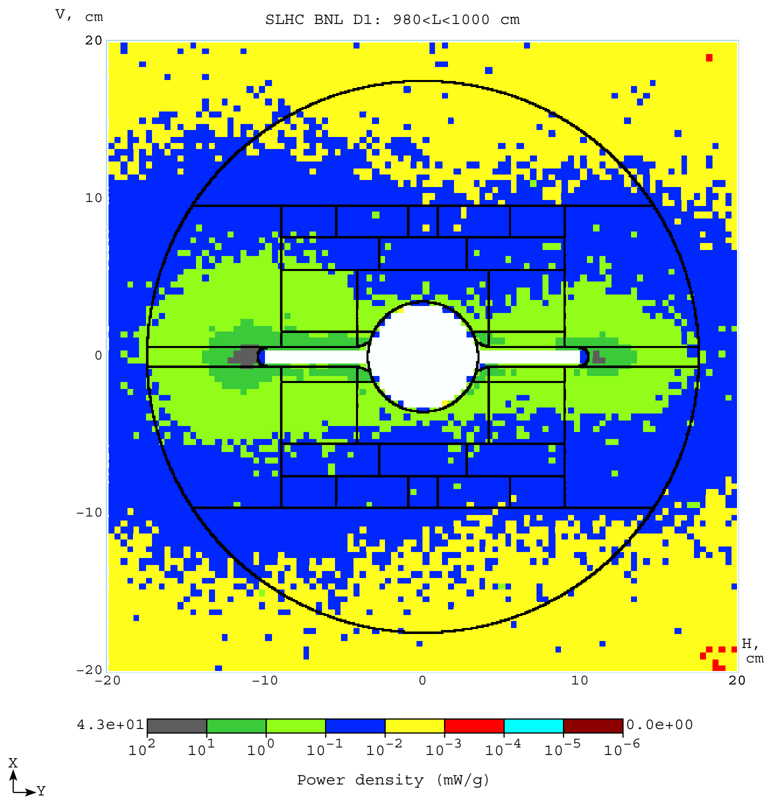




Peak power density is a factor of 100 higher in SLHC dipole ($\mathcal{L} = 10^{35}$) than in LHC IR quads ($\mathcal{L} = 10^{34}$).

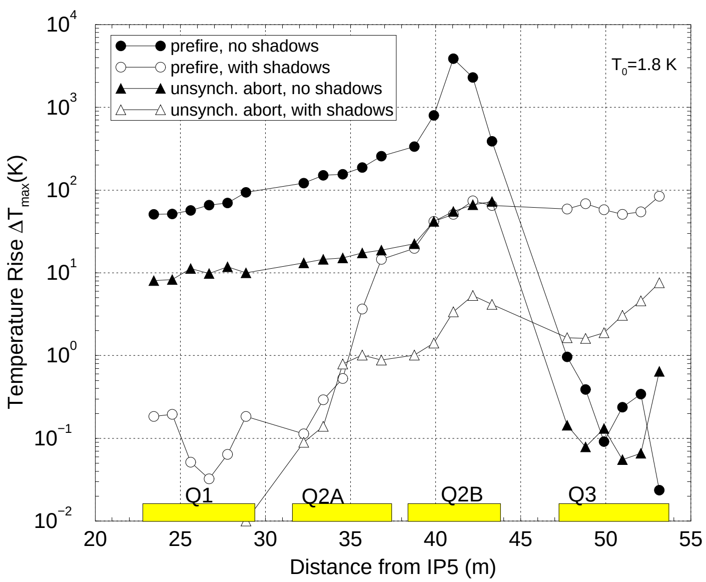
SLHS: DIPOLE-FIRST ENERGY DEPOSITION

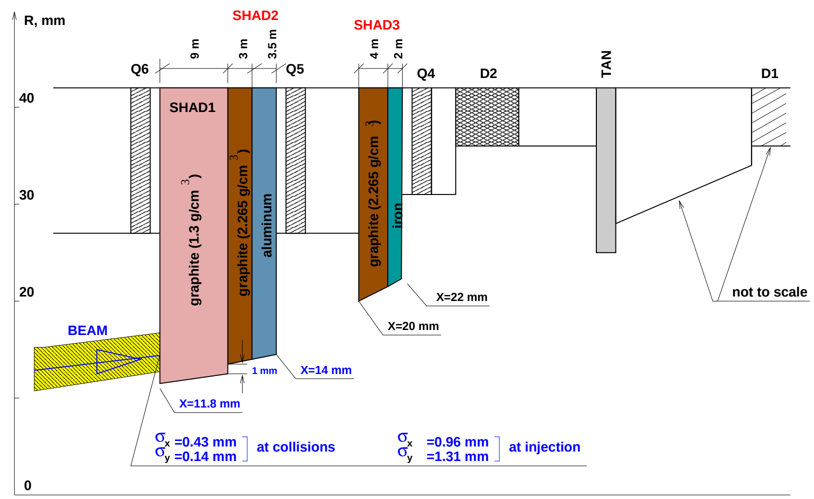




Peak power density is 49 mW/g in copper spacer and 13 mW/g in SC coil (left) and only 1.1 mW/g in the SC coils of block-type dipole (right). Total power dissipated in the dipole is 3.5 kW in either design.

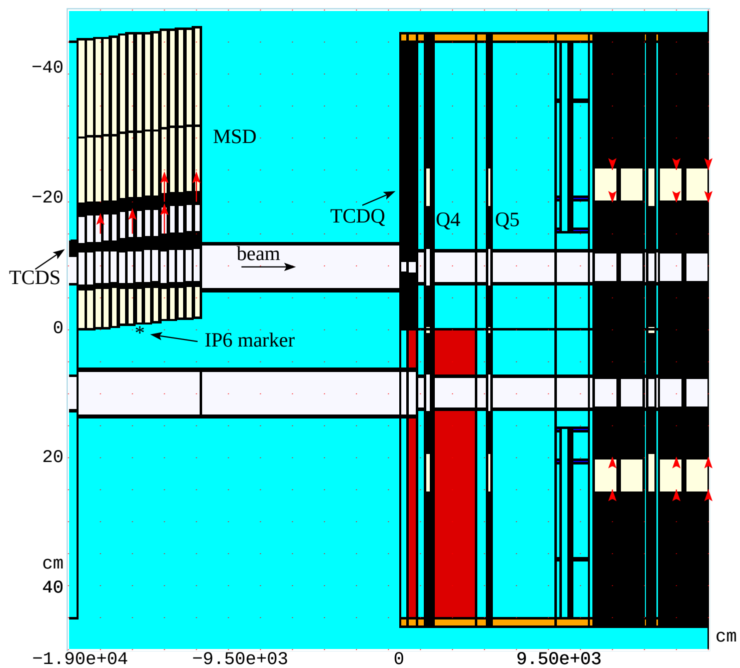
ACCIDENTAL BEAM LOSS (1)

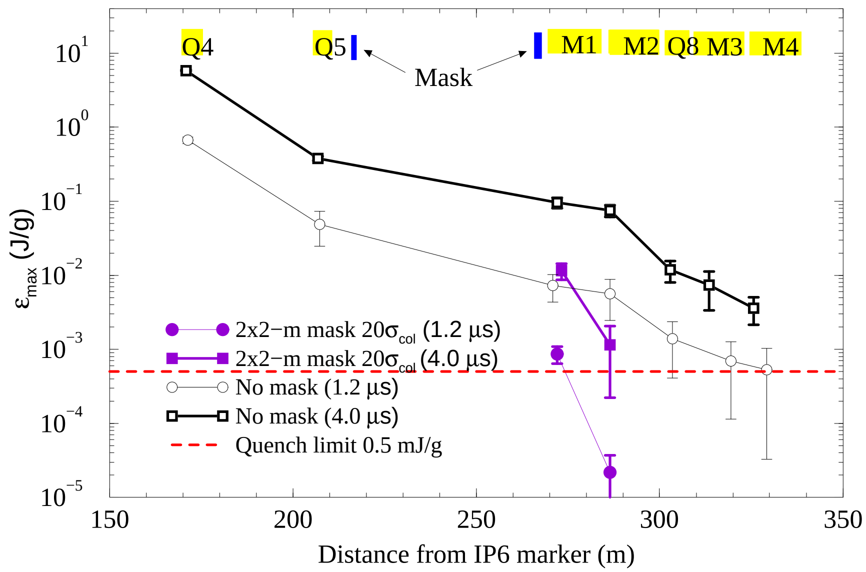




Peak temperature rise in the LHC IP5 inner triplet SC coils (left) and stationary collimators in the IP5 outer triplet (right).

ACCIDENTAL BEAM LOSS PROTECTION





LHC protection system with a movable collimator in IP6 (left) and peak energy deposition density ε_{max} in SC coils *vs.* distance from the IP6 marker, where M1 - M4 denote the first four dipoles (right).

UNCERTAINTIES

LHC, LHC-2 and SLHC: Based on numerous international benchmarking on micro and macro levels, status of the current event generators, thorough sensitivity analysis in the inner triplet over last seven years (event generators, physics other than event generators, geometry, materials, fields, crossing etc), numerous discussions and analyses of the results by the community over the same seven years, understanding of the Monte Carlo aspects, we would claim that we predict the maximum power density in the coils with an accuracy better than 30%. This should be true for the innermost layers of the SC coils (just a beginning of showers with almost no attenuation) for the *given* configuration, not for the one with possible changes. The uncertainty is higher at larger radii and larger distances from the IP, often because of statistics. Integral energy deposition and integral flux values in the components such as azimuthal average, power dissipation (dynamic heat load) are predicted with about 10-15% accuracy.

VLHC-1 and VLHC-2: A factor of 2 to 3 on top of that.

Residual dose rates are estimated within a factor of two to three at supercolliders.

CONCLUSIONS

1. We can keep a peak power density below the quench limit
   - in 90-mm 200-T NbSn3 quads at $\mathcal{L} \leq 2.5\times10^{34}$ with 30 W/m of dynamic heat load at peak (compared to 10 W/m now) in LHC;
   - in a 14-T NbSn3 dipole-first D1 at $\mathcal{L} \leq 1\times10^{35}$ with total power dissipated in the dipole of about 3.5 kW (!), with a superconductor-less mid-plane design.
2. All of the above, with a carefull design of TAS, intermediate absorbers and the near-beam region in D1.
3. $\sigma_p \times \mathcal{L}$ scaling gives a reasonable estimate, although details of spatial distributions can be obtained via realistic Monte Carlo. It turns out that there is no strong dependence of peak power density PD on the coil aperture because one needs to adjust the gradient appropriately.

4. Rules of thumb here are
   - at fixed aperture, the stronger field the higher PD;
   - at fixed field, the larger aperture the lower peak PD with heat load distributed more uniformly along the triplet with more secondaries (power) leaking towards its end and further (TAN and outer triplet).
5. As seen above, dynamic heat load is a serious issue.
6. Radiation issues are very serious at higher luminosities. Yes, we are below the quench limit in NbSn3, but it is a factor of few as large as that for present NbTi quads. But accumulated dose, residual dose rates and other radiation values inside and outside magnets scale up with luminosity, linearly to the first approach. With the present design, at $\mathcal{L} = 10^{34}$, we are on a 7-year limit for material life-time and on or above (!) the CERN limits for residual radiation. Much more MARS analysis is neded here on configuration and materials.

7. Operational and accidental beam loss in the inner and outer triplets is a serious issue, with their higher magnetic fields. The results we have for the current design are already somewhat scaring. We have a sophisticated monstrous movable collimator in IP6 to handle unsynchronized beam abort, but it seems that to reliably protect IP5 inner triplet we would still need anoter collimator on the non-IP side of the current D1. At SLHC everything becomes more severe.

8. TAS itself and shielding around TAS-Q1 need to be re-designed to suppress ten times (at least) higher albedo fluxes to ATLAS and CMS-like detectors.

9. Neutral beam absorber TAN and its shielding need to be re-designed to accomodate ten times higher beam power and provide adequate shielding for prompt and residual radiation.